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A COMPARATIVE STUDY AND ANALYSIS OF THE PERFORMANCE OF VARIOUS REGENERATIVE BRAKING SYSTEMS

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ABSTRACT

Regenerative Braking System (RBS) converts a part of the vehicle's kinetic energy into a useful form of energy. Thus the fuel requirements and the level of pollutants exhausted by the vehicle are reduced, and can be controlled. Various Regenerative Braking Systems include Mechanical Flywheel RBS, Elastomeric Flywheel RBS, Hydraulic Power-Assist RBS, Ultra capacitor RBS, etc. In this paper, a typical mathematical analysis of the performance of Mechanical flywheel RBS, Elastomeric Flywheel RBS, and Hydraulic Power-Assist RBS has been studied on different car models based on current research, and a comparison of the efficiencies and fuel savings by these systems has been done taking into consideration, a basic Volvo car model. Analysis shows the efficiencies of Elastomeric Flywheel RBS, Hydraulic Power-Assist RBS, and Mechanical Flywheel RBS will be in a descending order.

Key words: Efficiency, Elastomeric Flywheel RBS, Hydraulic Power Assist RBS, Mechanical Flywheel RBS, Regenerative Braking System.

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THRUST AND MOTIVATION FOR THIS STUDY

The initial stimulus for undertaking study in regenerative braking system was personal interest. Rising pollution and environment concerns has also brought this novel energy saving

concept in the spotlight. This paper encompasses the majorly used regenerative system installed on hybrid vehicles.

PROBLEM STATEMENT

To analyse the parameters affecting the performance of RBS and compare their efficiencies to select the best RBS system for a given Light Motor Vehicle (LMV).

1. INTRODUCTION

Today as we are on the path of technological advancement, various countries are on the verge of exploiting the natural reserves to harness energy, and sustain in the competition. Hence, the world reserves of petroleum products, oil and natural gas are drastically reducing. There are 1.3 trillion barrels of proven oil reserves left in the world's major fields, which at present rates of consumption will last around 40 years. Burning fossil fuels produces around 21.3 billion tonnes of carbon dioxide per year, and only half of that is absorbed by natural processes. The result is catastrophic, increasing global warming and causing the average surface temperature of the planet to rise.

The highest share of energy consumption in the world is of the Automobile Sector. Thus, wide research is being going on to make automobiles consume lesser amount of fuel, and reduce the resulting harmful effects on the environment.

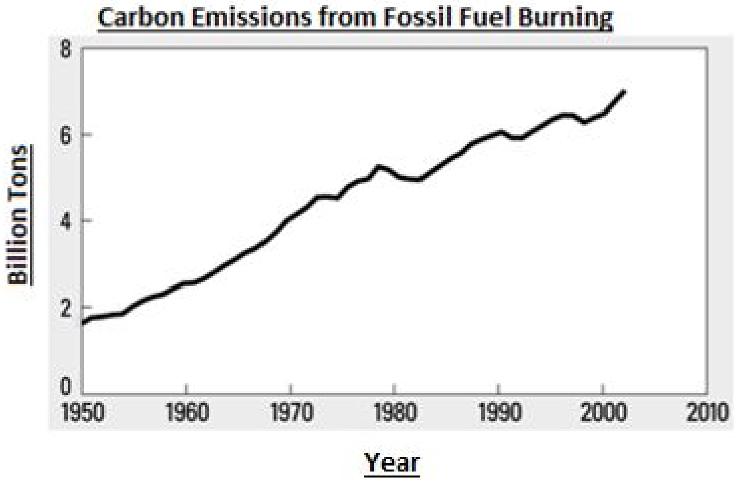

Figure 1 Graph of Carbon Emissions from Fossil Fuel burning

2. REGENERATIVE BRAKING

Contrary to conventional friction braking, in regenerative braking, a part of the kinetic energy (KE) of the vehicle is converted into useful form of energy.

This stored energy is then used in future as per requirement and the dynamic conditions prevailing. Without Regenerative braking the whole of KE is converted into friction and heat, which is a total loss.

The regenerative systems considered for comparison in this paper are:

- Mechanical Flywheel Regenerative Braking System
- Elastomeric Flywheel Regenerative Braking System
- Hydraulic Power-Assisted Regenerative Braking System

2.1. Mechanical Flywheel RBS System

This regenerative braking system is a type of a conventional system. During light and gradual braking, the kinetic energy of the system is stored in the form of rotational kinetic energy of the flywheel. This energy is then given back to the system when it is required for the vehicle to accelerate. The basic parts of this system are flywheel, gearbox and a clutch system. The flywheel is enclosed in an evacuated chamber to avoid friction losses and also for safety issues. The flywheel weighs around 8-10 kg depending on the weight of the vehicle. The flywheel rotates at high RPMs and when power is required, the clutch is engaged and the power is transmitted to the wheels through the gearbox [1].

The wheel of the vehicle is connected to the secondary pulley of Continuously Variable Transmission (CVT) through a clutch arrangement. The primary pulley of the CVT is further connected to the flywheel fixed gearing through another clutch. This fixed gearing is permanently connected to the flywheel of the vehicle. Thus a two-step gear transmission is present in this system. Thus, the overall gear ratio $G_{overall}$is-

$$G_{overall} = G_{fixed\ flywheel\ gearing} * G_{CVT}$$

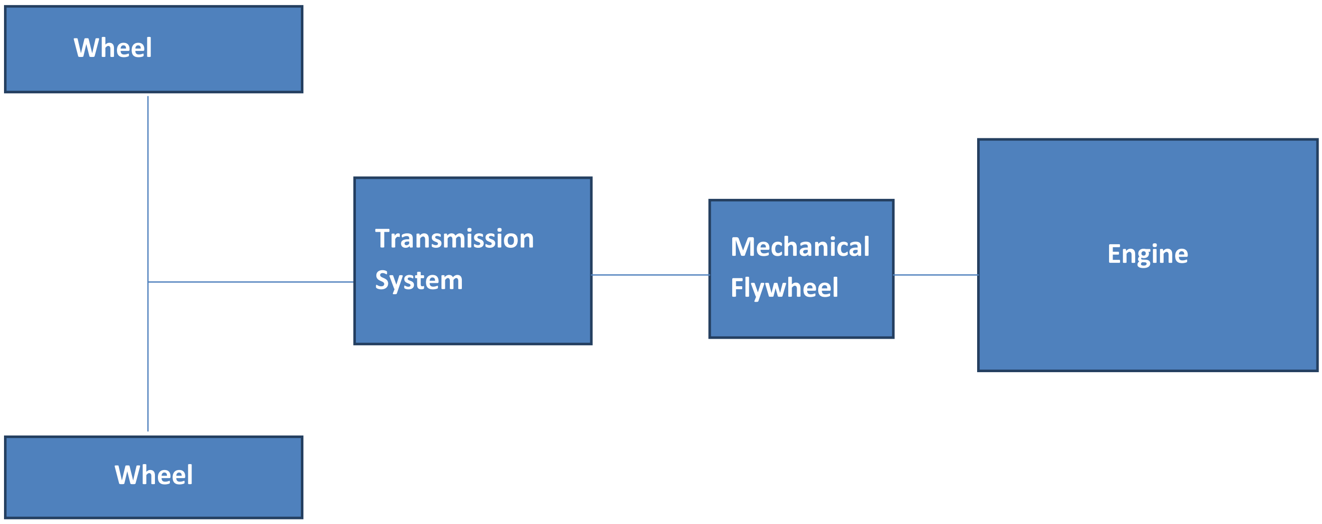

Figure 2 Mechanical flywheel RBS

2.2. Elastomeric Flywheel RBS System

This system is an improvement over the existing conventional flywheel system [6]. The flywheel is made up of composite material. As the speed of the flywheel increases, the flywheel expands due to the elastic nature of the material used. Due to this, the Moment of inertia of the flywheel increases and compared to the conventional rigid flywheel system, more energy can be stored. The system of the elastic flywheel has the same components as the conventional flywheel system [7].

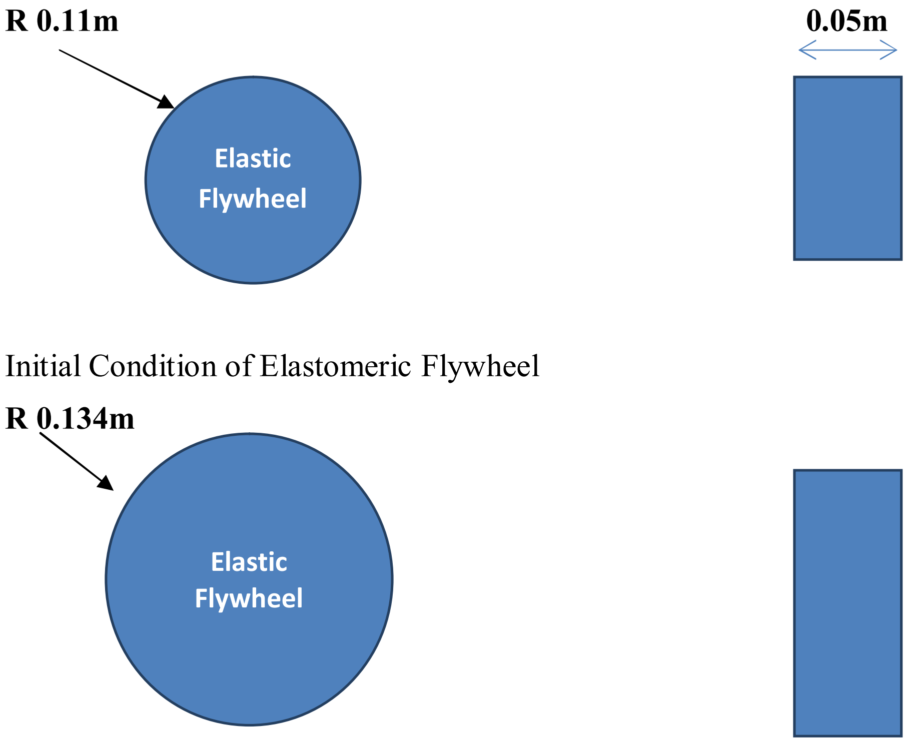

Figure 3 Increased radius of Flywheel at maximum angular velocity

2.3. Hydraulic Power-Assisted RBS System

Hydraulic power assist is a type of regenerative braking system which stores the kinetic energy of the vehicle in the form of pressurized hydraulic fluid. This pressurized energy which is stored in the high pressure accumulator is released when required for extra boost. When the vehicle starts regenerative braking, the pump uses rotational energy of the driveshaft and pumps oil from low pressure accumulator to high pressure accumulator. The high pressure accumulator has a pre-charge of nitrogen gas. This pre-charge is further pressurized when oil is pumped form the low pressure accumulator. As and when the vehicle will require boost, pressurized fluid is released through a poppet valve. The pump then acts as a motor where this stored energy is given to the driveshaft through a gearbox.

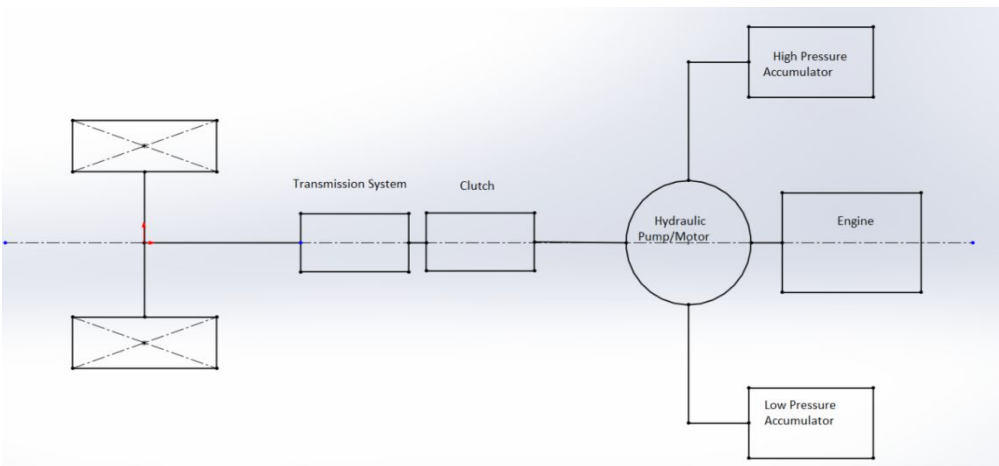

Figure 4 Hydraulic Power-Assisted Regenerative Braking System Configuration Diagram

3. NOMENCLATURE

m = mass of the vehicle

$m_w = mass\ of\ wheel$

$v_w = initial\ velocity\ of\ the\ vehicle$

$r_w = radius\ of\ the\ vehicle\ tyre$

$I_w = moment\ of\ inertia\ of\ the\ tyre$

$\omega_w = angular\ velocity\ of\ the\ tyre\ \left(\frac{rad}{s}\right)$

$I_f = moment\ of\ inertia\ of\ the\ flywheel\ (kg - m^2)$

$\omega_f = angular\ velocity\ of\ flywheel\ (rad/s)$

$\varrho = density\ of\ flywheel\ (kg/m^3)$

$t_f = thickness\ of\ flywheel\ (m)$

$m_f = mass\ of\ flywheel\ (kg)$

$r_{f0} = initial\ radius\ of\ flywheel\ (m)$

$I_{f0} = initial\ moment\ of\ inertia\ of\ flywheel\ (kg - m^2)$

$r_{f1} = final\ radius\ of\ flywheel\ (m)$

$L_1 = I_1 \times \omega_1 = initial\ angular\ momentum\ of\ vehicle\ \left(kg - \frac{m^2}{s}\right)$

$L_2 = I_2 \times \omega_2 = initial\ angular\ momentum\ of\ flywheel$

$L_1^1 = I_1^1 \times \omega_1^1 = final\ angular\ momentum\ of\ vehicle$

$L_2^1 = I_2^1 \times \omega_2^1 = final\ angular\ momentum\ of\ flywheel$

$E_{acc} = Energy\ stored\ inside\ the\ accumulator$

$P_{min} = Minimum\ working\ pressure\ of\ accumulator$

$P = Pressure\ inside\ the\ accumulator\ at\ any\ instant\ or\ at\ any\ particular\ condition$

$V_1 = Volume\ of\ gas\ at\ minimum\ working\ pressure$

$v = Average\ vehicle\ speed$

$n = Polytropic\ Index$

$P_1, V_1 = Pressure - Volume\ conditions\ in\ the\ first\ position$

$P_2, V_2 = Pressure - Volume\ conditions\ in\ the\ second\ position$

$P_3, V_3 = Pressure - Volume\ conditions\ in\ the\ third\ position$

4. ANALYSIS OF RBS SYSTEMS

4.1. Mechanical Flywheel RBS System

The following observations have been noted after system testing of Mechanical Flywheel RBS System installed on a car as specified in [3]. Three cases of regenerative braking and three cases of acceleration have been covered in the test. Further analysis of these observations has been done as follows:

Case	1	2	3	4	5	6
Wheel Initial Velocity(m/s)	16.9875	12.964	12.516	16.095	12.295	16.095
Wheel Final Velocity(m/s)	13.411	13.858	15.647	12.964	15.2	12.7417
Flywheel Initial Speed(rpm)	3500	7300	6600	3200	6670	3507
Flywheel Final Speed(rpm)	7295.815	6319.89	2976.634	6677.187	3771.596	6945.954
Initial Gear Ratio	5.48	14.36	14.02	5.3	14.4	5.8
Final Gear Ratio	14.47	12.13	5.06	13.7	6.6	14.5
Time(sec)	1.214	0.27	0.99	1.015	0.953	1.08

Analysis of Table

Case 1- This is a case of regenerative braking.

Wheel Condition	Initial	Final
Speed (km/hr)	61.155	48.28
Speed (m/sec)	16.9875	13.411
Angular velocity of wheel (rad/sec)	66.88	52.8

Therefore,

Change in Kinetic Energy of wheel $\Delta K.E. = \Delta\frac{1}{2} mv^2 + \Delta\frac{1}{2}I\omega^2$

$= (\frac{1}{2}mv_1^2 - \frac{1}{2}mv_2^2) + (\frac{1}{2}I\omega_1^2 - \frac{1}{2}I\omega_2^2)$

$= [\frac{1}{2}(150)(16.9875^2) - \frac{1}{2}(150)(13.411^2)]$

$+[\frac{1}{2}(10.1)(66.88^2) - \frac{1}{2}(10.1)(52.8^2)]$

Change in Kinetic Energy of wheel = 16.6637 KJ (1)

Flywheel Condition	Initial	Final
Speed (rpm)	3500	7295.815
Angular velocity (rad/sec)	366.519	764.016

Therefore,

Change in Kinetic Energy of Flywheel = $\Delta \frac{1}{2}I\omega^2$

$=\frac{1}{2}I\omega_2^2 - \frac{1}{2}I\omega_1^2$

$=\frac{1}{2}[0.038] [(764.016^2) - (366.519^2)]$

Change in Kinetic Energy of Flywheel = 8.5383 KJ (2)

Therefore, Fraction of energy absorbed by the flywheel, off the total energy lost by the wheel

$= \frac{8.5383}{16.6637}$

= 0.51239 or 51.239% (3)

Similarly, solving the cases 2 to 6, the result of these 6 cases has been shown below:

Case	1 (braking)	2 (acceleration)	3 (acceleration)	4 (braking)	5 (acceleration)	6 (braking)
% energy absorbed by flywheel, off the total energy lost by the wheel	51.239 %	---	---	51.326 %	---	50.547 %
% energy required by the wheel to accelerate, that is supplied by flywheel	---	75.64 %	53.5 %	---	51.488 %	---

Hence, from the above system, we can conclude that-

- Out of total energy loss of wheels in braking, about 51 % of the energy is absorbed by the flywheel.
- During acceleration, the mechanical flywheel provides nearly 60 % of the energy requirement of the wheel.

In the given mechanical system, two flywheel RBS systems have been installed on the vehicle, and hence the effective weight on each system will be half the weight of the vehicle.

Due to similarities in the relative parameters of the vehicle mentioned in [3] and Volvo S60, further analysis on Volvo S60 has been done.

For Volvo S60 model,

Moment of Inertia of Flywheel = $I_f = \frac{1}{2} m_f r^2 = \frac{1}{2}(8)(0.1^2) = 0.04$ kg-m^2.

Moment of Inertia of wheel = 70.363 kg-m^2.

Considering regenerative braking from 22.22 m/sec to 0 m/sec ,

Change in Kinetic Energy of wheel = $\Delta\frac{1}{2} mv^2 + \Delta\frac{1}{2} I\omega^2$

$= [\frac{1}{2}(1045)(22.22^2) - \frac{1}{2}(1045)(0^2)] +$

$[\frac{1}{2}(70.363)(111.1^2) - \frac{1}{2}(70.363)(0^2)]$

Change in Kinetic Energy of wheel = 692.2256 KJ

Hence, according to conclusions of Case 1-6 , Energy absorbed by the flywheel of Volvo S60 during regenerative braking from 22.22 m/s to 0 m/s = 51% of 692.2256 KJ

= 0.51*692.2256

Energy absorbed by the flywheel = 353.035 KJ

When the flywheel is used during acceleration , the velocity 'v' that can be attained by the car using the energy stored by the flywheel is given by the equation which can be referred in [4] & [5]–

$\frac{1}{2}mv^2 + \frac{1}{2}I\omega^2 = 353035$ J

$\frac{1}{2}(1045)v^2 + \frac{1}{2}(70.363)(\frac{v}{0.2})^2 = 353035$

Therefore, solving the quadratic equation and neglecting the negative root, we get,

v = 15.868 m/sec.

Thus, after braking from 22.22 m/sec to 0 m/sec using mechanical flywheel regenerative braking system, we can accelerate the car back up to 15.868 m/sec.

Efficiency of the mechanical flywheel system is given by

$$\eta = \frac{\frac{1}{2}\times m\times v^2}{\frac{1}{2}\times m\times v_w^2} = \frac{(15.868)^2}{(22.22)^2}, \eta = 50.99\%$$

4.2. Elastomeric Flywheel Calculations

Natural Rubber has been selected as the material for Elastomeric Flywheel. The following parameters are required for analysis of Elastomeric Flywheel RBS System.

$$m = 2090kg v_w = 22.22m/s r_w = 0.2m \varrho = 930 \left(\frac{kg}{m^3}\right) t_f = 0.05\ (m)$$

4.2.1. Calculations

$$Density\ of\ flywheel = mass\ of\ flywheel \div volume$$

$$m_f = \varrho \times A \times t_f$$

$$m_f = 930 \times \Pi \times 0.11 \times 0.11 \times 0.05 = 1.7676\ kg$$

$$I_{f0} = \frac{1}{2} \times m_f \times r_f^2 = \frac{1}{2} \times 1.7676 \times 0.11 \times 0.11$$

$$I_{f0} = 0.01069\ kg - m^2$$

$$I_w = \frac{1}{2} \times m_w \times r_w^2 = 70.363\ kg - m^2$$

$$\omega_w = \frac{v_w}{r_w} = \frac{22.22}{0.2} = 111.11\ rad/s$$

$$\omega_f = 11925\ rad/s$$

By law of conservation of angular momentum

$$L_1 + L_2 = L_1^1 + L_2^1$$

$$7818.03 = 70.363 \times \frac{v_w}{r_w} + 1053.315 \times r_w^2$$

$$351.815 \times v_w + 10539.315 \times r_f^2 = 7818.03 \qquad (1)$$

By law of conservation of energy

$$\eta \left[\frac{1}{2} \times I_f \times \omega_f^2\right] = \frac{1}{2} \times m_w \times v^2 + 1/2 \times I_w \times (\frac{v_w}{r_w})^2$$

$$\frac{1}{2} \times \eta \times m_w \times r_f^2 \times 11925^2 = 2090 \times v^2 + \left(\frac{70.363}{0.2^2}\right) \times v^2$$

$$100545065.1 \times r_f^2 = 2090 \times v^2 + 1759.075 \times v^2$$

$$r_f^2 = 0.000038282 \times v^2$$

$$r_f = 0.006187 \times v \qquad (2)$$

Substituting equation (2) in equation (1), we get

$$351.815 \times v + 0.4025 \times v^2 = 7818.05$$

$$v = 21.684\ m/s$$

Substituting the above value in equation (2)

$$r_f = 0.134m$$

Efficiency of the elastomeric flywheel system is given by

$$\eta = \frac{\frac{1}{2} \times m_w \times v^2}{\frac{1}{2} \times m_w \times v_w^2} = \frac{(21.684)^2}{(22.22)^2}$$

$$\eta = 95.23\%$$

5. HYDRAULIC POWER ASSIST

The three different systems of regenerative braking have been compared on the basis of the final velocity attained by the car and the overall efficiency of the system.

5.1. Calculations

The HPA System used for the analysis has been derived from [8] .The following values have been taken for calculating the efficiency of the Hydraulic Power Assist (HPA) system:

$$P_{min} = 172\ barm = 2090kg$$
$$P = 344\ barn = 1.4$$

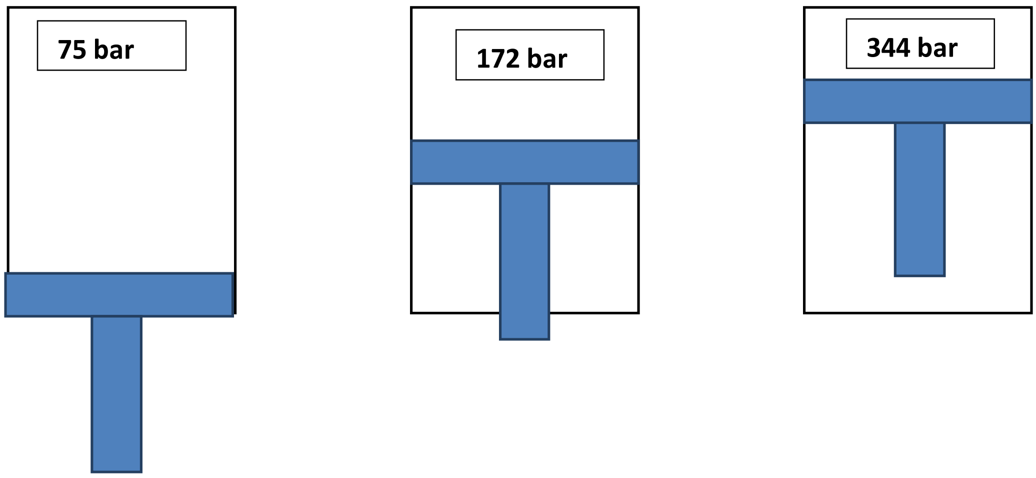

Figure 5 Different positions of piston inside the accumulator

Three different positions of the piston inside the accumulator are shown. The first position corresponds to the pre-charge pressure of the nitrogen gas inside the accumulator. The second and the third positions correspond to the minimum and maximum working pressure inside the accumulator.

$$P_1V_1^n = P_2V_2^n = P_3V_3^n$$
$$(75)(0.00545)^{1.4} = (172)V_2^{1.4} = (344)V_3^{1.4}$$
$V_2 = 0.0030125$ m^3, and$V_3 = 0.001836$ m^3

The energy stored inside the accumulator is given by the equation:

$$E_{acc} = \frac{P_{min} \times V_1}{n-1} \times [\left(\frac{P_{min}}{P}\right)^{\frac{1-n}{n}} - 1] \geq \frac{1}{2} \times m \times v^2$$

$$\frac{172 \times 10^5 \times 30.125 \times 10^{-3}}{1.4 - 1} \times \left[\left(\frac{172}{344}\right)^{\frac{1-1.4}{1.4}} - 1\right] = \frac{1}{2} \times 2090 \times v^2$$

$$v = 16.476\frac{m}{s}$$

Efficiency of the Hydraulic Power Assist system is given by:

$$\eta = \frac{1/2 \times m \times v^2}{1/2 \times m \times v_1^2}$$

$$v_1 = Initial\ velocity\ of\ the\ vehicle$$
$$\eta = 54.981\%$$

6. CONCLUSION

As can be seen from the calculations above, after braking from a speed of 22.22 m/sec to 0 m/sec and accelerating using the stored energy by the system, the velocity that can be attained using these systems has been evaluated for all the three RBS systems mentioned in this paper. The velocity attained by these systems during acceleration, and the efficiency of the respective RBS system have been tabulated below.

RBS System used	Velocity attained using the stored energy by the RBS system during acceleration	Efficiency of the RBS System
Mechanical Flywheel RBS	15.868 m/sec	50.99%
Elastomeric Flywheel RBS	21.684 m/sec	95.23%
Hydraulic Power Assist	16.476 m/sec	54.98%

- The results above have been obtained by installing these three RBS systems on a car model-Volvo S60.
- Observing the results obtained, it can be concluded that the efficiency of Elastomeric Flywheel RBS System is the highest for Volvo S60, followed by Hydraulic Power-assisted and Mechanical Flywheel RBS Systems. So, Elastomeric Flywheel RBS System would be the best choice of RBS System for Volvo S60 model.
- The above method of calculations can also be used as a reference to analytically evaluate the best RBS System for any other automobile model, just by replacing the specifications of Volvo S60 car model with the new automobile model to be considered.

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